Basic physics of the first wall

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Outline

- Why wall is important
- Plasma-material interaction phenomena
- Modeling methods
- Dynamic wall

Introduction

Plasma-facing surfaces:

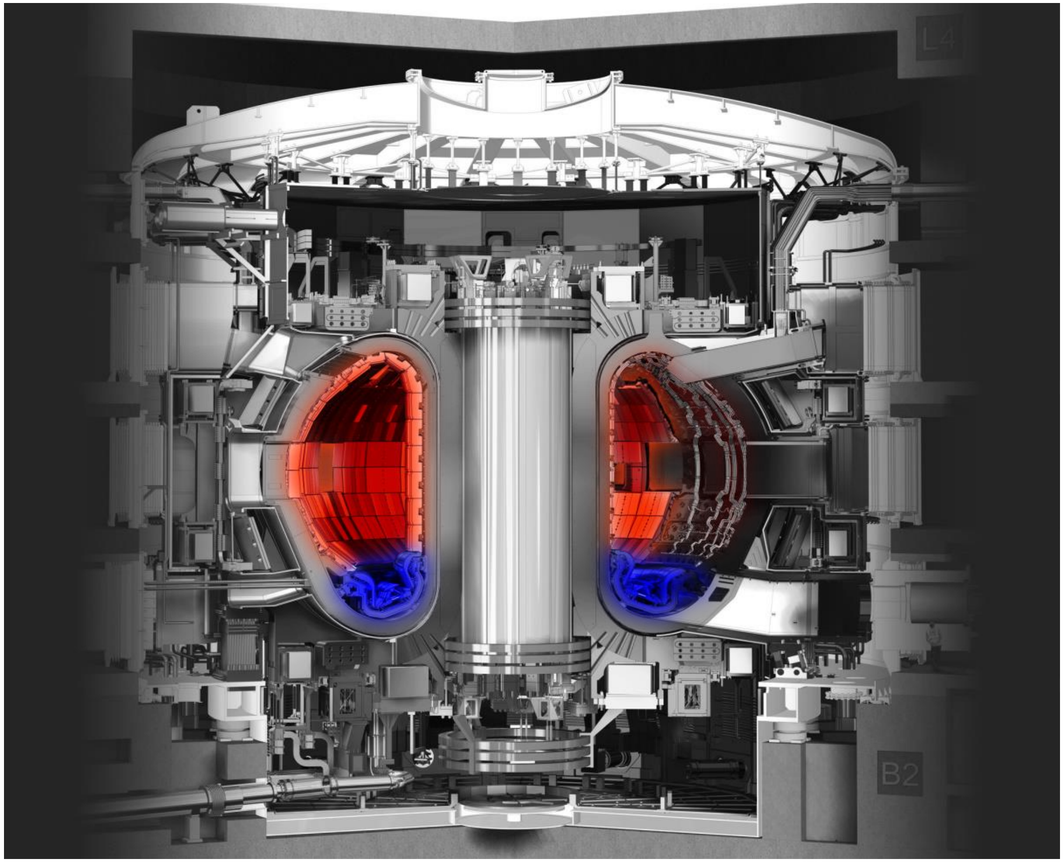
- First wall (Be, Li, Cu, St.st.)
- Divertor (W, St.st.)

Experimentally known that wall conditioning can drastically improve fusion performance:

- Decrease of impurity influx
- Better control of plasma density

However, what is physics behind these effects?

ITER tokamak

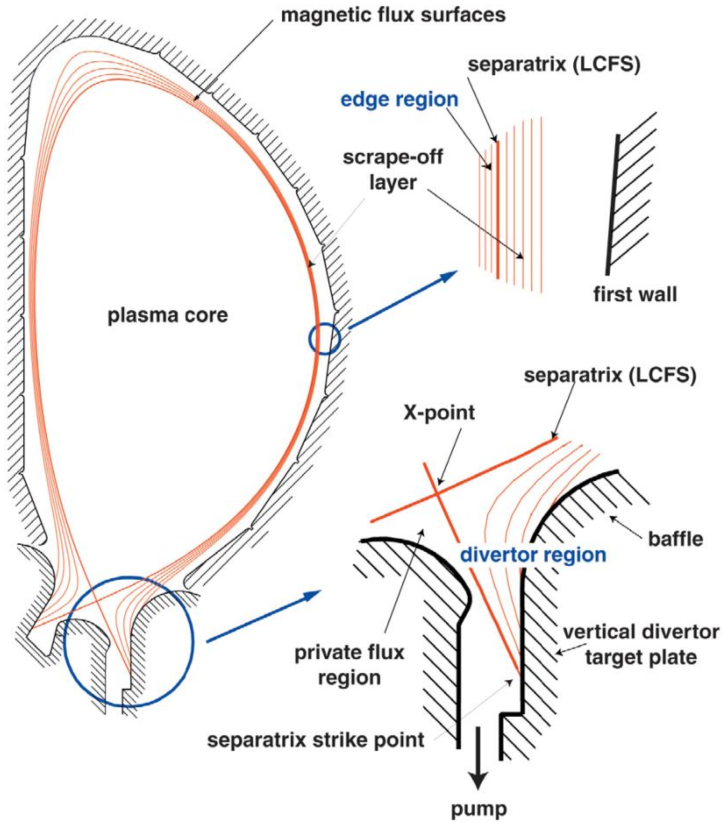


Key issues

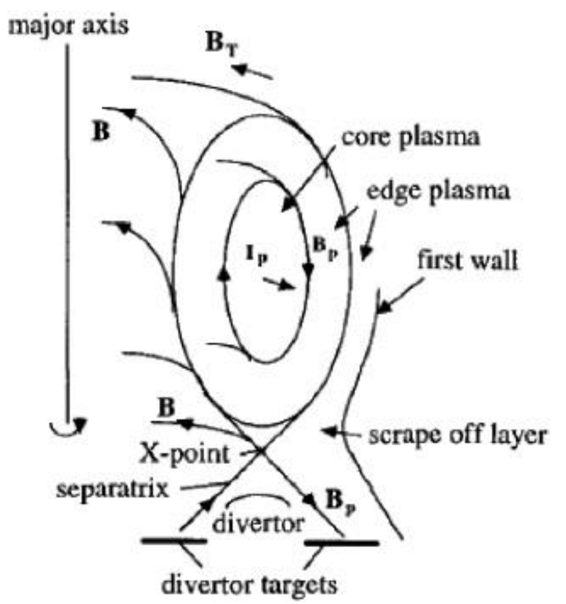
First wall and divertor materials will need to handle various (generally very high) plasma particle and power fluxes in fusion reactors

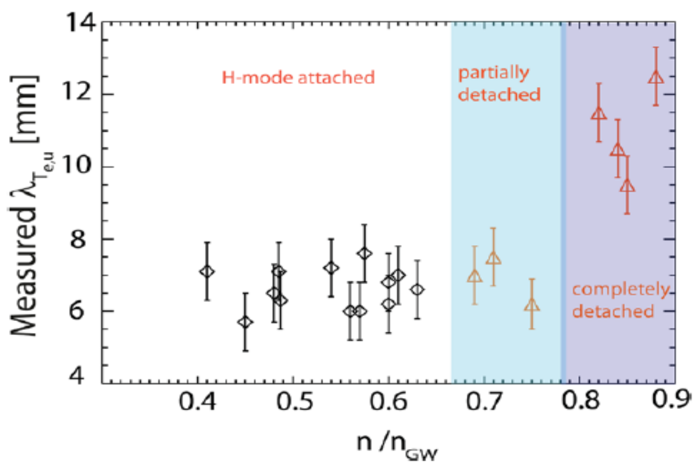
- Heat removal
- Erosion / plasma contamination
- Trituim uptake / outgassing
- He exhaust
- Neutron damage
- Dust production
- Degradation of material properties

	Wall	Divertor
Peak heat flux, MW/m^2	0.5-2	10-20
Particle flux, $1/m^2s$	$\sim10^{20}$	$\sim10^{24}$
Energy, eV	100-500	1-30
Neutron flux, dpa/year	~3-50	



Scrape-off-Layer





H.J. Sun et al., *PPCF* **57** (2015) 125011

Transport of particle and heat fluxes from and to the core plasma across and along **B** occurs in SOL

Power fluxes from core to SOL:

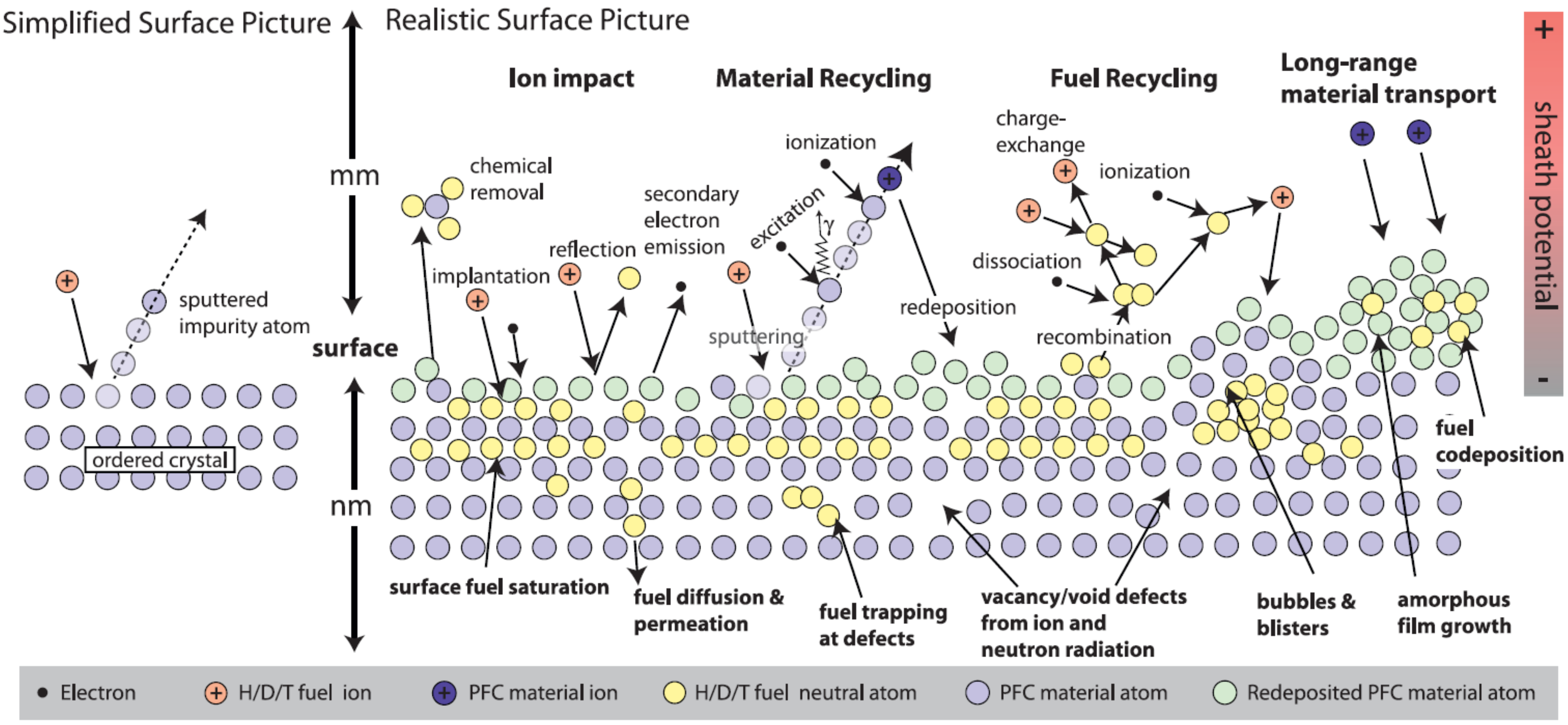
- steady state ~100MW
- transients (ELMs) ~10MJ,>GW

SOL width:

- several mm
- determines wetted area
- depends on anomalous transport in SOL, divertor plasma regime

Basic physical processes

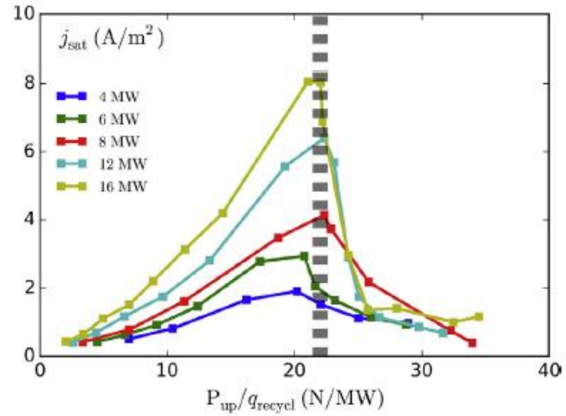
Interactions of plasma with the materials are very complex and multifaceted affecting both plasma and wall



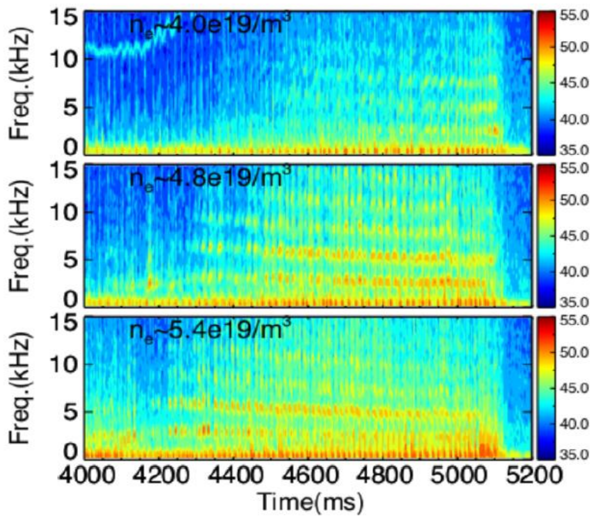
Phenomena in SOL

Plasma-material interactions have impact on plasma far from the wall

- Atomic and molecular processes (ionization, excitation, charge exchange, dissociation, recombination)
- Plasma recycling on material surfaces (supports plasma pressure, detached plasma regime)
- Radiation of wall eroded impurities (reduces SOL heat fluxes, may cause core cooling)
- SOL plasma instabilities (radiation-condensation, current-convective instability)



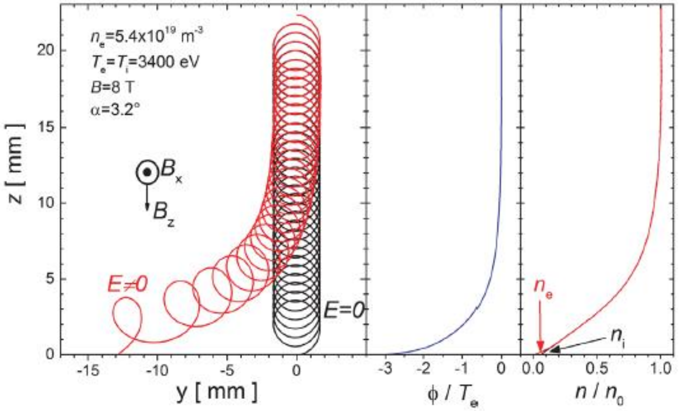
A.A. Pshenov et al., NME **12** (2017) 948



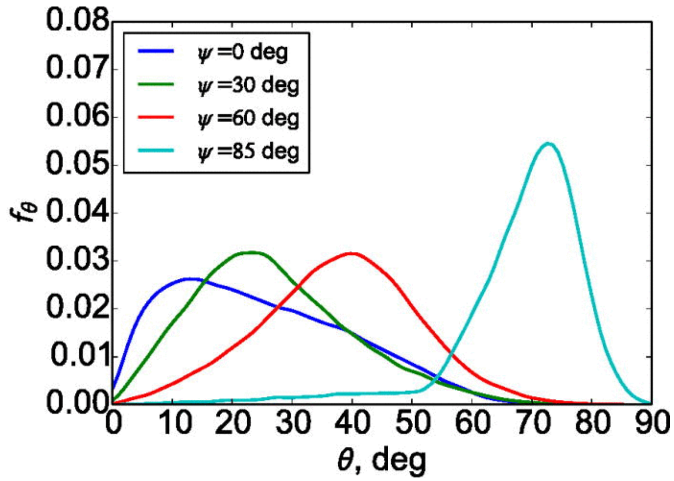
A.A. Stepanenko et al., *45th EPS* (2018) P2.1103

Sheath region

Plasma sheath develops near the wall due to difference in electron and ion velocities



J.P. Gunn et al., *Nucl. Fusion* **57** (2017) 046025

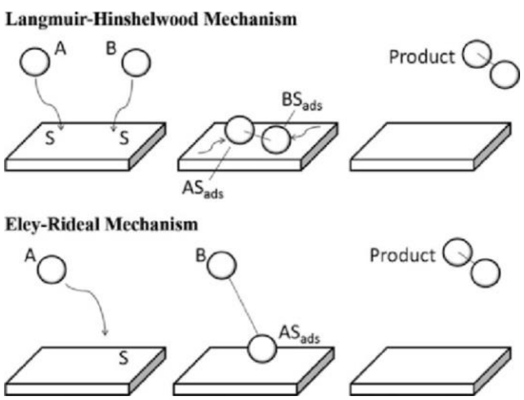


R. Khaziev and D. Curreli, *PoP* **22** (2015) 043503

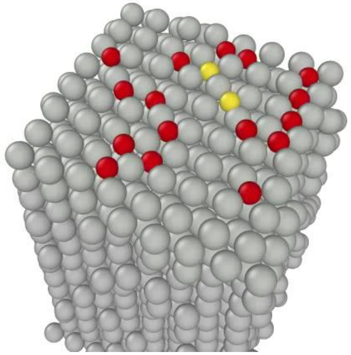
- Ion acceleration, drifts (affects impact energy and angle distributions)
- Secondary electron and thermionic (alters sheath potential)
- Unipolar arcing
- Dust mobilization
- Prompt re-deposition of sputtered atoms
- Depend on surface morphology

Material surface

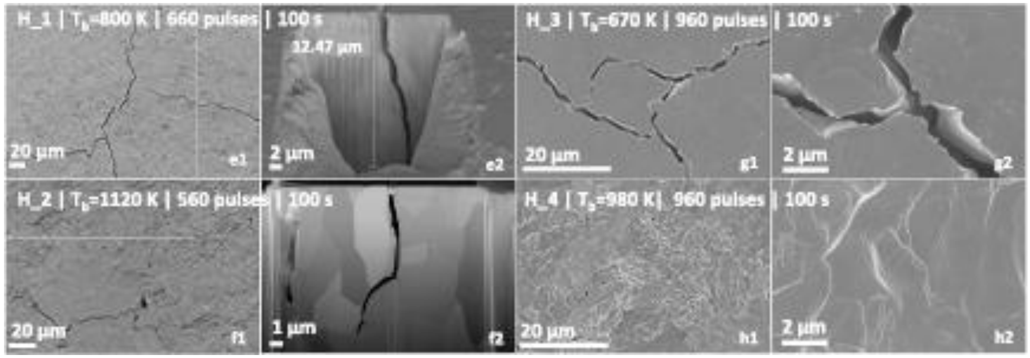
- Neutralization
- Backscattering
- Gas adsorption / desorption
- Material erosion /deposition
- Morphology changes / fuzz growth



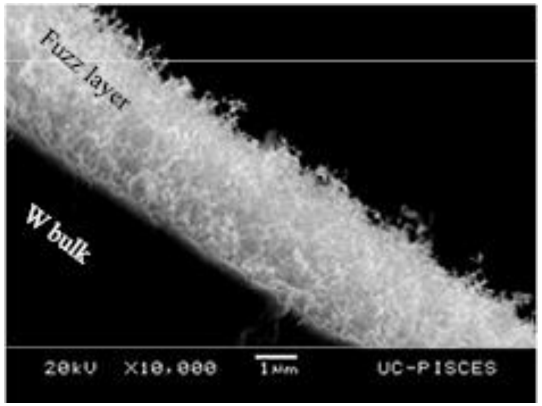
W <110> at T=1300K (EAM potential)



J. Guterl et al., Poster 6, Thursday



L. Buzi et al., Nucl. Fusion **57** (2017) 126009

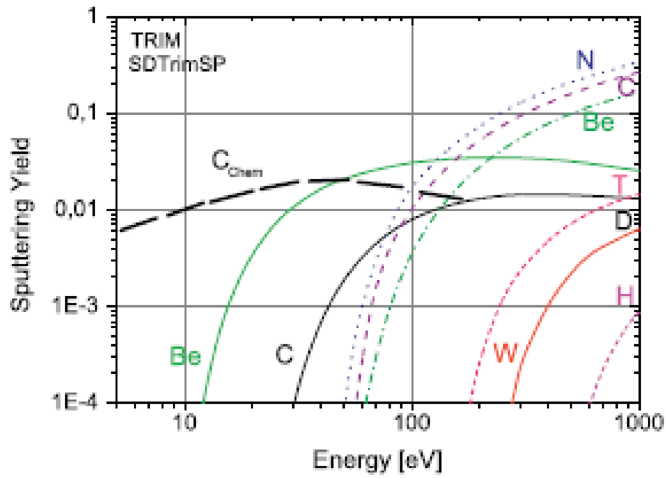


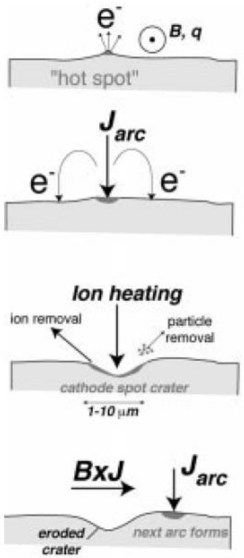
R.P. Doerner et al., *Nucl. Fusion* **58** (2018) 066005

Erosion

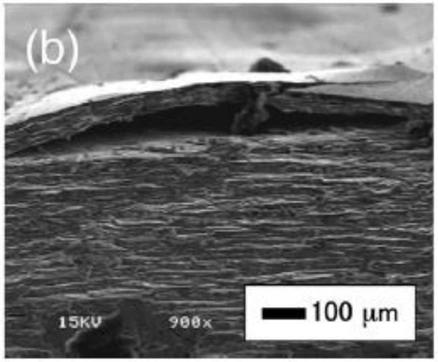
PFC erosion is the main source of fusion plasma impurities

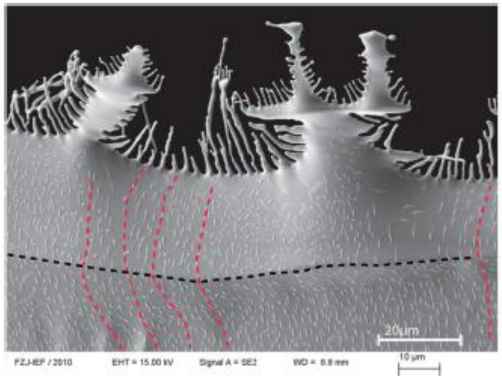
- Sputtering by D/He (physical, chemical, RES)
- Self-sputtering
- Delamination of deposits
- Blistering
- Cracking
- Arcing
- Grain ejection
- Melt layer ejection (JxB forces)





S. Brezinsek et al., JNM **463** (2015) 11

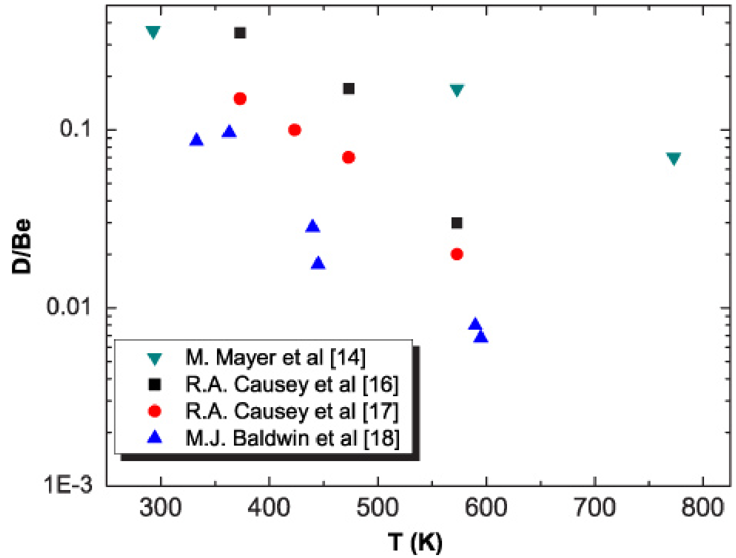




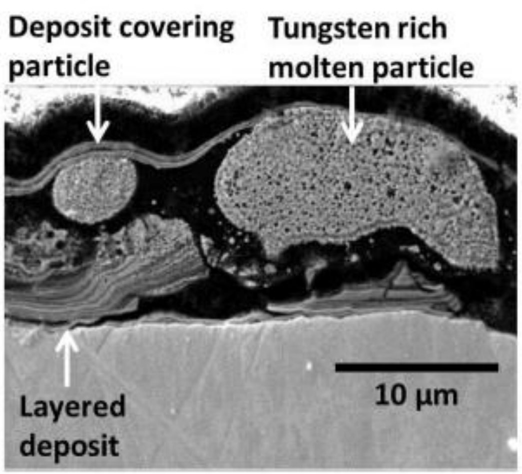
N. Ohno et al. JNM **363–365** (2007) 1153
J.W. Coenen *et al* 2011 *Nucl. Fusion* **51** 083008

Deposition

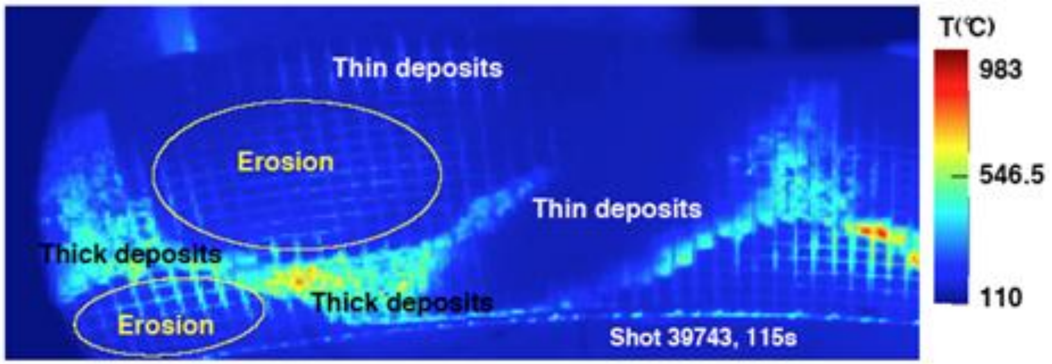
- D/T retention (Be co-deposits H/Be up to ~0.3)
- Mixed material formation (Be/W alloy, low T_{melt})
- Hot spot formation (causes large impurity/hydrogen emission)



G. De Temmerman et al., Nucl. Fusion **48** (2008) 075008



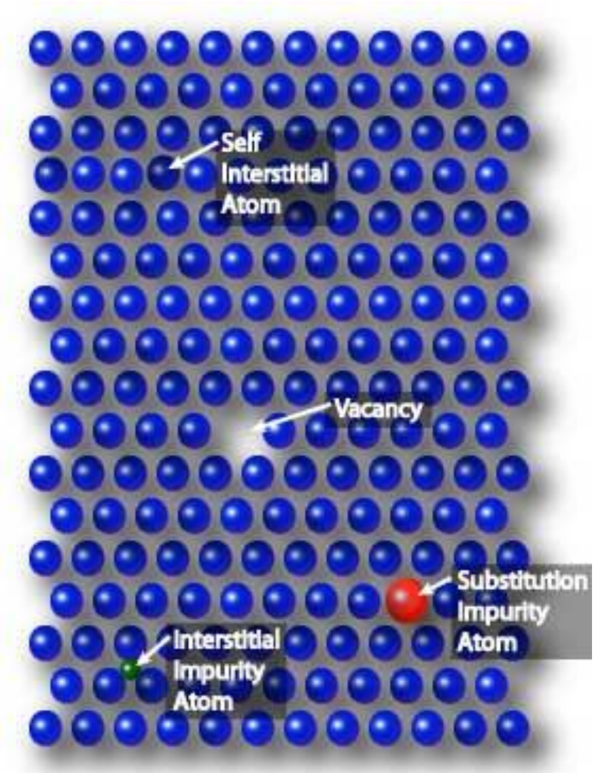
A. Widdowson et al., NME 12 (2017) 499



E. Tsitrone *et al* 2009 *Nucl. Fusion* **49** 075011

Material bulk

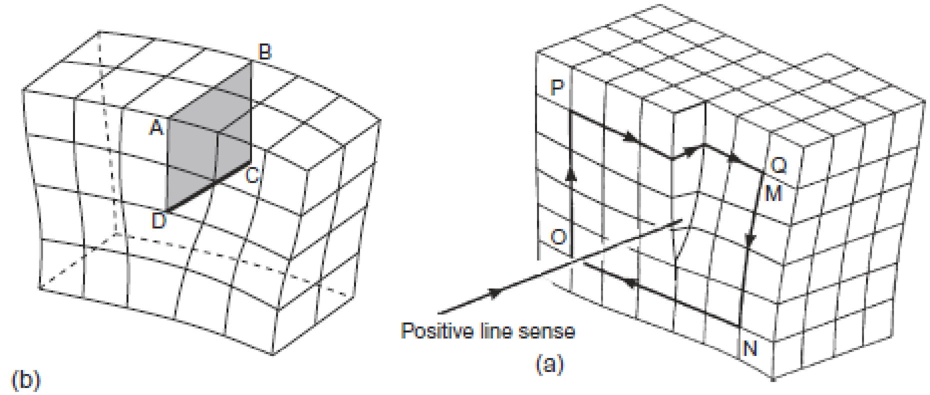
There are various imperfections in crystalline structure of metals

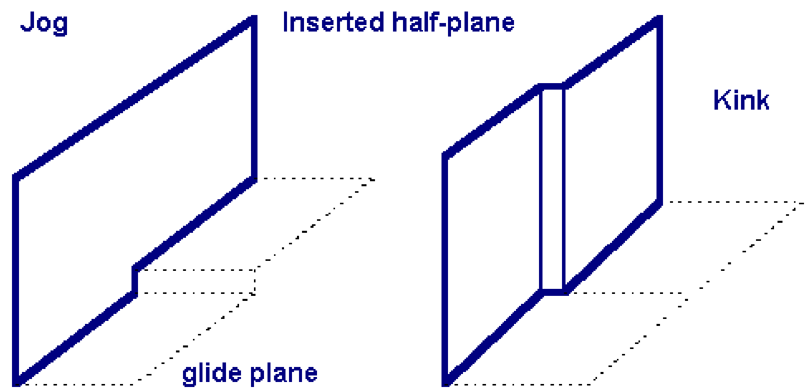


Point defects

edge dislocations

screw dislocations



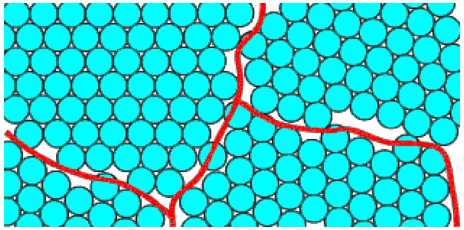


Linear defects

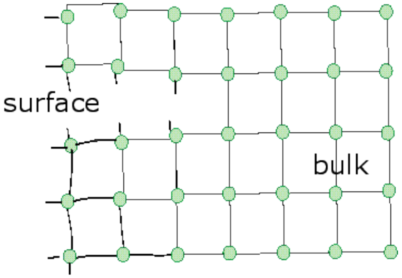
Material bulk

Crystalline structure of metals naturally has various imperfections

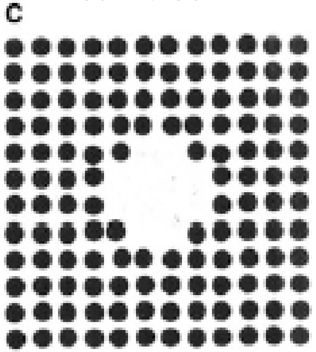
grain boundaries



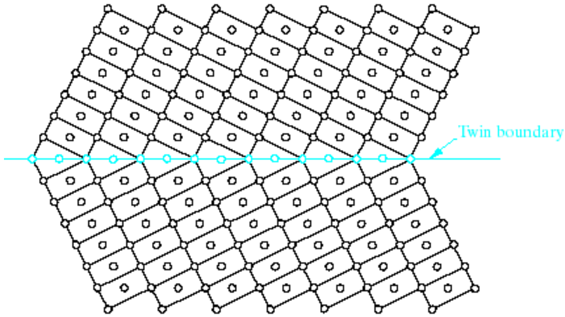
micro-cracks



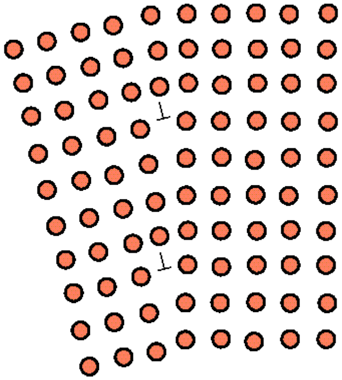
cavities



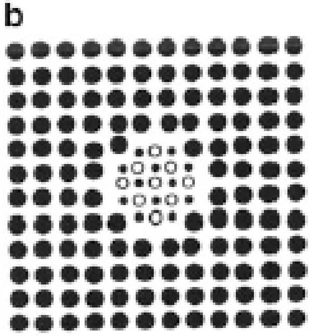
twin boundaries



tilt boundaries



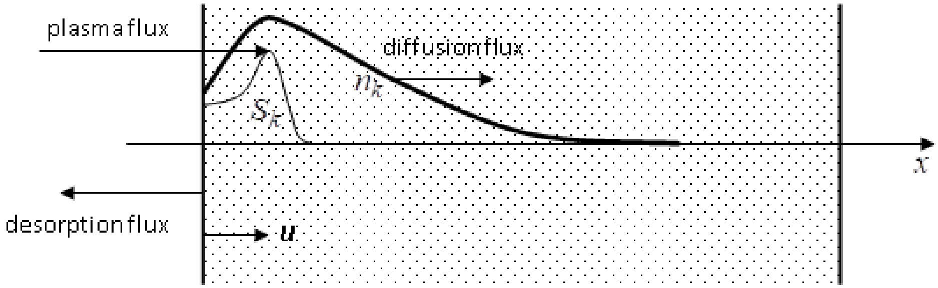
precipitates

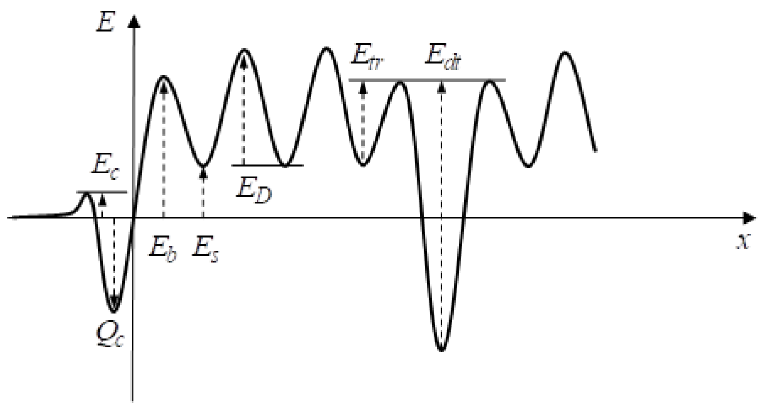


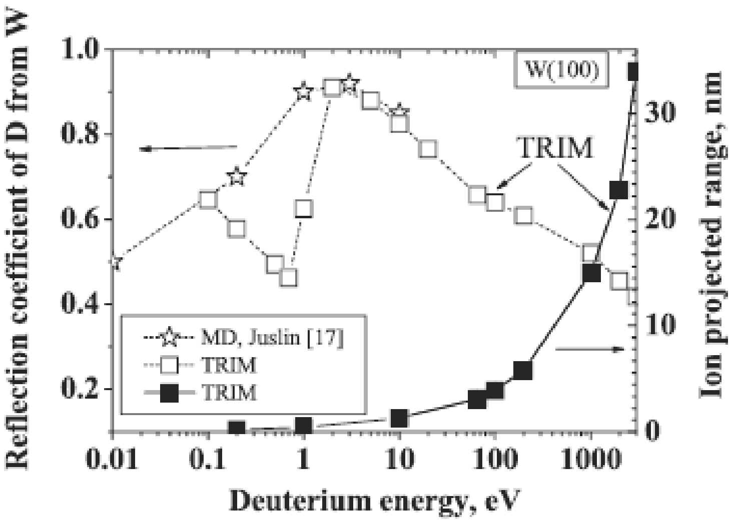
Planar defects

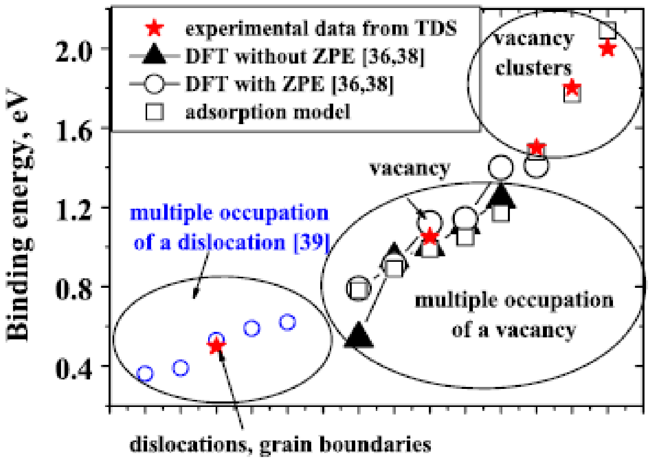
Volume defects

Transport in bulk





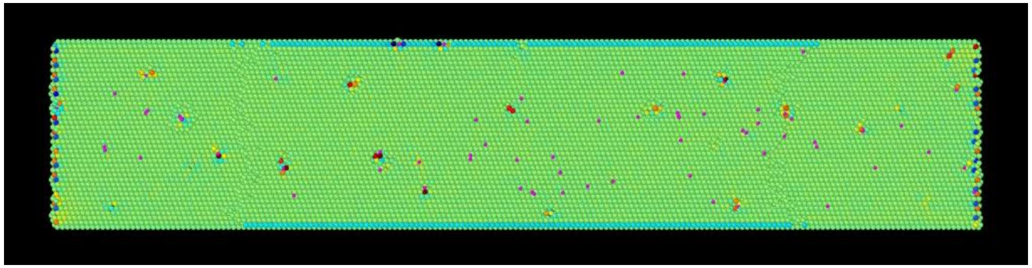


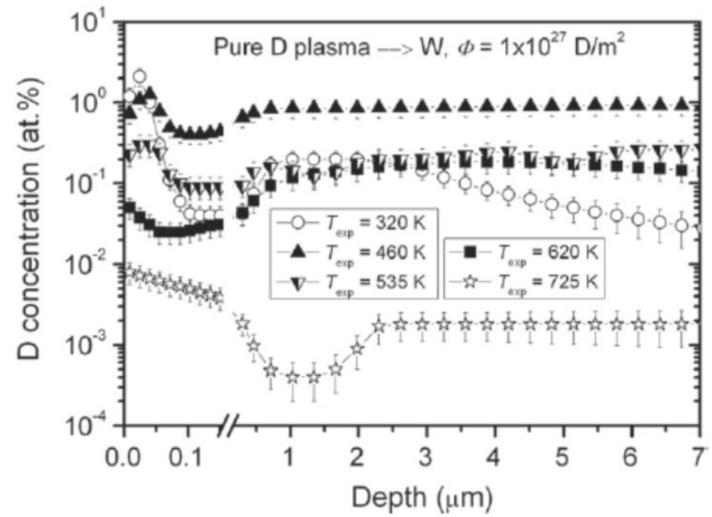


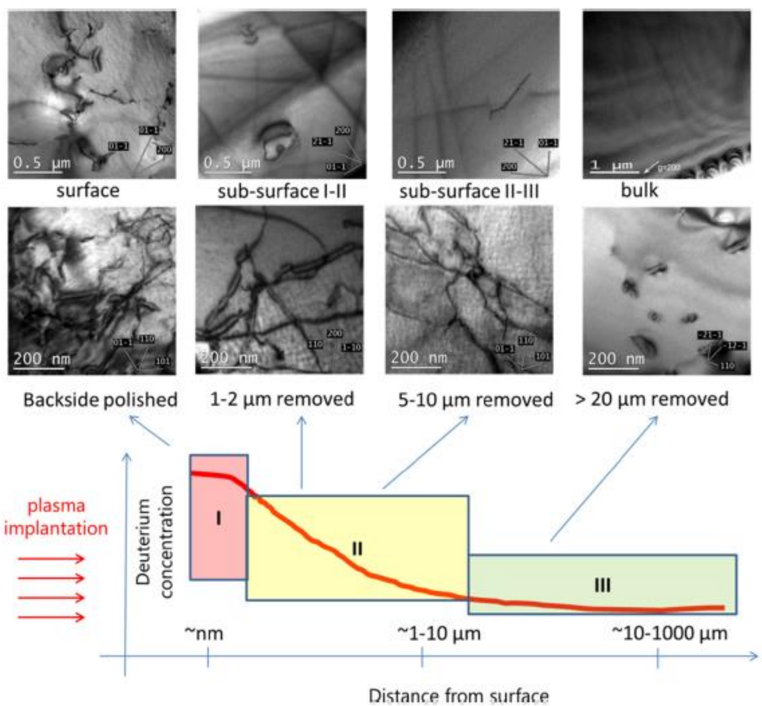
- Ion implantation depth (~several nm)
- D/He trapping on defects
- Effective diffusion (re-trapping, grain boundaries)

O.V. Ogorodnikova 2015 *J. Appl. Phys.* **118** 074902

Transport complications





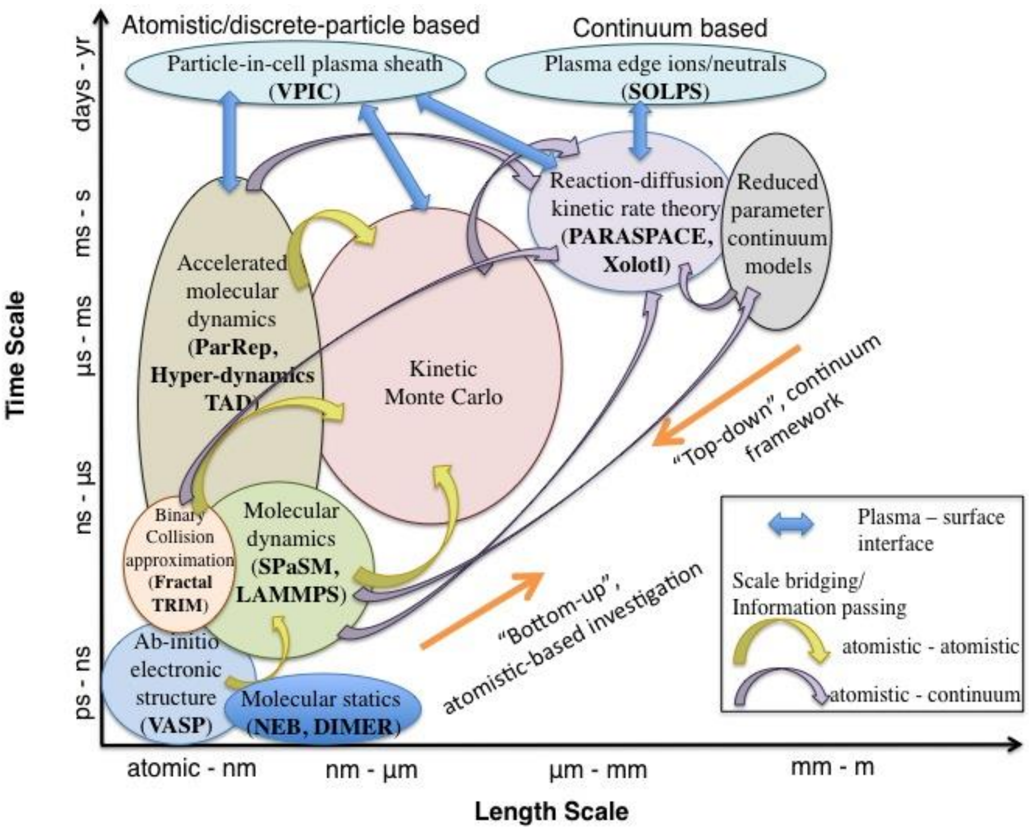


D. Terentyev et al. 2017 *Fusion Eng. Des.* **124** 405

- Induced defect formation and propagation
- Limited mobility of trapped H/He
- Saturated layer (tens of nm)
- Internal stresses, drifts
- Neutron damage, transmutations

Modeling methods

- Density Functional Therory (DFT)
- Molecular Dynamics (MD)
- Binary Collision
- Kinetic Monte-Carlo (KMC)
- Reaction Diffusion (RD)
- Particle-in-Cell (PIC)
- Fluid plasma transport (including atomic physics)

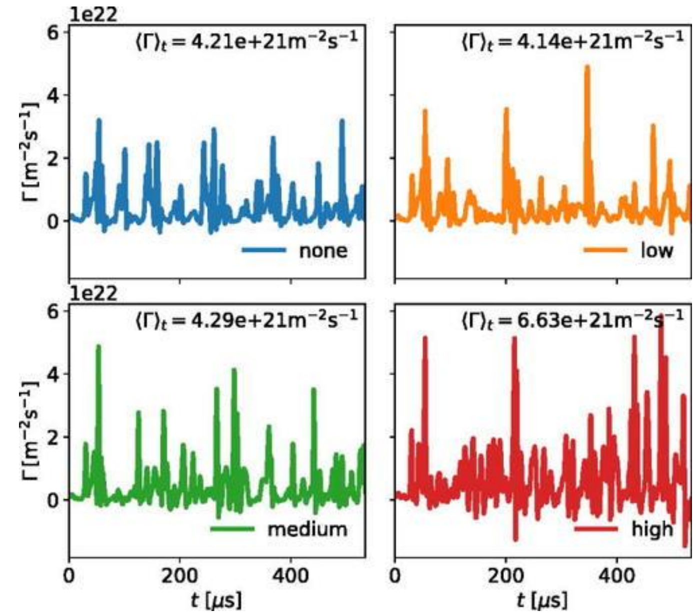


Argonne National Laboratory; DIII-D National Fusion Facility; Los Alamos National Laboratory; Oak Ridge National Laboratory; Pacific Northwest National Laboratory; Illinois; UC San Diego; UMass Amherst; Sandia National Laboratories; Rensselaer; Lawrence Livermore National Laboratory

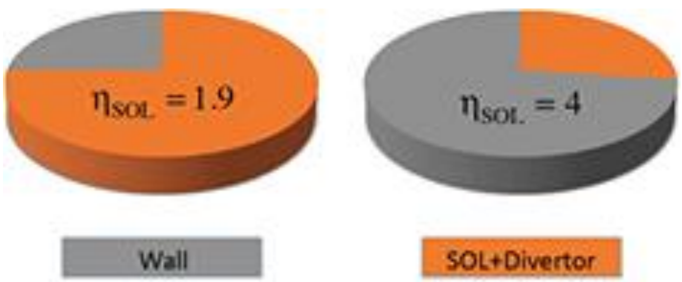
SciDAC-PSI Project ***"Bridging from the Surface to the Micron Frontier through Leadership Computing"***

Wall impact on turbulence

- Blobby spikes are increasing in amplitude and frequency with increase of neutral density
- Neutrals affect edge plasma turbulence spectra in both SOL and divertor plasmas (*f* decreased)
- Wall outgassing plays central role in pedestal recovery after large ELM
- Neutral gradients may cause Raleigh-Taylor type of instabilities in divertor
- Neutral transport and ionization effects can cause negative “generalized” plasma-neutral diffusion (density growth)



A. S. Thrysøe et al., PoP **25**, 032307 (2018)



S.I. Krasheninnikov et al., PPCF **57** (2015) 044009

$$\eta = \Delta N_{ped}/N_{SOL+div}$$

Modeling dynamic wall

Approximate method to study coupled plasma-wall linear stability

$$\hat{F}^{p}_{w}\{\delta j_w(t)\} = \delta j_p(t),$$ Functional response of plasma flux to wall

$$\hat{F}^{w}_{p}\{\delta j_p(t)\} + \hat{\Phi}^{R}_{w}\{\delta j_w(t)\} = \delta j_w(t).$$ Functional response of neutral flux from wall

$$\hat{F}^{w}_{p}\left\{\hat{F}^{p}_{w}\{\delta j_w(t)\}\right\} + \hat{\Phi}^{R}_{w}\{\delta j_w(t)\} = \delta j_w(t).$$

In stationary equilibrium, decompose fluxes into time Fourier integral (ω) and toroidal series (n)

Numerical simulations with small perturbations

$$\begin{cases} \hat{F}^{p}_{w}\{\sin(\omega t)\} = j^{s}_{wp}(\omega)\sin(\omega t) + j^{c}_{wp}(\omega)\cos(\omega t) \\ \hat{F}^{p}_{w}\{\cos(\omega t)\} = j^{s}_{wp}(\omega)\cos(\omega t) - j^{c}_{wp}(\omega)\sin(\omega t), \end{cases}$$

$$\begin{cases} \hat{F}^{w}_{p}\{\sin(\omega t)\} = j^{s}_{pw}(\omega)\sin(\omega t) + j^{c}_{pw}(\omega)\cos(\omega t) \\ \hat{F}^{w}_{p}\{\cos(\omega t)\} = j^{s}_{pw}(\omega)\cos(\omega t) - j^{c}_{pw}(\omega)\sin(\omega t), \end{cases}$$

$$\begin{cases} \hat{\Phi}^{R}_{w}\{\sin(\omega t)\} = j^{s}_{wR}(\omega)\sin(\omega t) + j^{c}_{wR}(\omega)\cos(\omega t) \\ \hat{\Phi}^{R}_{w}\{\cos(\omega t)\} = j^{s}_{wR}(\omega)\cos(\omega t) - j^{c}_{wR}(\omega)\sin(\omega t), \end{cases}$$

Dispersion equation

$$\hat{D}_{pw}(\omega, n) = 0,$$

$$\pm i\{j^{c}_{wp}(\omega)j^{s}_{pw}(\omega) + j^{s}_{wp}(\omega)j^{c}_{pw}(\omega) + j^{c}_{wR}(\omega)\}$$
$$= 1 - j^{s}_{wp}(\omega)j^{s}_{pw}(\omega) + j^{c}_{wp}(\omega)j^{c}_{pw}(\omega) - j^{s}_{wR}(\omega),$$

No real ω solutions

S.I. Krasheninnikov, *PoP* **25** (2018) 064501

Conclusions

- Plasma-wall interactions play essential role in magnetic fusion devices and are very multifaceted
- There is experimental and numerical evidence clearly demonstrating the synergistic effects of plasma-wall interactions on edge plasma transport and wall conditions
- Studies of plasma-wall interactions require combination of large array of analytical and computational methods
- There is new physics to uncover